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Assessing buildings' absolute environmental sustainability performance using LCA focusing on climate change impacts

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Abstract. The building sector is of major concern when seeking to reduce the environmental impact of our society. A common tool often used in certification systems for quantification of environmental impacts is Life Cycle Assessments (LCAs). LCAs are traditionally used for relative comparisons, i.e. to assess whether one product or service performs better than another. Recently, a method for absolute evaluations based on the Planetary Boundaries, was coupled with LCA in order to define the boundary between environmental sustainability and unsustainability. In this study Planetary Boundaries-based Life Cycle Impact Assessment method has been applied to a case study of six single family stand-alone dwellings to assess whether these buildings can be considered absolute sustainable relative to the Planetary Boundaries. The results from the assessment indicate that irrespective of the design strategy used for the six houses and future increase in the use of renewables for electricity and heat production, it is unlikely that any of these houses can be regarded as sustainable in absolute terms. This underlines that more radical changes are needed in the way buildings are constructed and used in order for buildings to become environmentally sustainable.

1. State of the building industry

Every single step of a building's life cycle induces environmental impacts. Resources are extracted for the production of building components and energy is used during construction. When the building is in use, maintenance and repairs require the extraction of more resources for new building components, not to mention the energy required to keep the building heated and ventilated. Finally, when the service life of the building ends, components become waste that needs to be handled. In Europe, current construction of buildings account for 36 percent and 40 percent of the CO_2 emissions and energy consumption respectively [1]. By 2030 the global construction market is expected to increase by 85% to $15.5 trillion worldwide [2]. The Danish building industry produces 4.1 million ton waste every year, or a third of all waste produced in Denmark [3]. The reason for this is the fact that material waste from buildings is rarely used in new buildings or refurbishments. In most cases, the material waste is incinerated or landfilled and in best cases, reused or recycled [3].

However, the concept of circular economy, where fewer virgin resources are extracted and waste is considered a pool of resources, is becoming more widespread and is more often integrated into design strategies and influences the choice of materials [4]. By now some buildings are being designed for disassembly to allow for easier reuse of components and in impact-heavy building materials such as insulation and concrete the virgin raw materials are partially or completely replaced by recycled materials [5, 6]. In 2012, an adapted version of the German building sustainability certification system DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) was introduced to the Danish building industry [7]. A certification system such as DGNB offers the possibility to measure and compare the environmental performance of buildings against specified benchmarks, and this has contributed dramatically to raising awareness of sustainability in the building industry. In 2013, life cycle thinking was introduced in the building certification system LEED in the form of life cycle assessment (LCA) as an optional assessment step to improve the overall rating of a building. In DGNB a full LCA of the building is mandatory [8].

LCA is an environmental performance assessment methodology that allows for relative environmental assessment, i.e. assessment of product A's performance compared to that of product B [9]. LCA is a framework most often used to claim environmental superiority of products relative to another or to identify environmental hotspots in a product's life cycle. Building LCAs, in present certification practice, assess buildings relative to benchmarks representing (best) current building practice [10]. However, the evaluation does not relate to whether absolute sustainability is actually reached. The term sustainability is becoming increasingly broad in its meaning, and if our actions towards limiting climate change are to be successful, it is crucial that we still aim for a sustainable development as originally defined in the Brundtland report, namely "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [11]. Hence, there is a need for an absolute perspective, where we do not burden the planet with our actions more than the planet is able to cope with/compensate for.

The goal of this study is to evaluate whether or not the current approaches to sustainable building design are in fact sustainable. This is done by applying a so-called absolute environmental sustainability assessment. It should be noted that the impact scope of this paper has been limited to climate change impacts.

2. Absolute environmental sustainability assessment

In absolute environmental sustainability assessments (AESAs), environmental boundaries are used for setting the boundary between environmental sustainability and unsustainability as the environmental boundaries are used to indicate whether or not environmental systems and processes are able to cope with the environmental burden associated with a product or as in this study, a single family stand-alone dwelling. In this AESA, the Planetary Boundaries (PBs) [12] where used as absolute environmental boundaries. The Planetary Boundaries define a safe operating space that all human activities need to stay within to ensure that the carrying capacity of the Earth System processes are not compromised [13]. Impacts associated with the dwelling were quantified in the metrics of the PBs by performing an LCA and using the Planetary Boundaries-based Life Cycle Impact Assessment method [13]. Once quantified, the impact scores where related to the PBs. However, as the PBs accounts for the global Earth System processes (i.e. all people and all impacts irrespective of origin), the share of the safe operating space available for each dwelling needs to be assigned and the dwelling's impact score should be related to the assigned share of the safe operating space to determine whether the dwelling can be considered absolute sustainable [14]. There is no objective approach to share the safe operating space among activities, as it is an issue of quantifying *who* has the right to impact *how much*. In order to simplify this, only one approach for assigning the safe operating space is considered in this paper, but other approaches exist and the specific choice of sharing principle could yield different results.

In this study, the safe operating space was shared using an egalitarian and utilitarian approach. First, the global safe operating space was shared among global population (7.63×10^{-9}) using equal per capita approach (egalitarian). Next, the personal share assigned to the household was found using data on final consumption expenditure to determine the share of income that people in Denmark spend on their household relative to other products and services (giving a share of 0.571 [8]). This is an utilitarian approach as it was assumed that personal spending habits are adequate indicators of which products and services brings the largest utility to people. Next, the household share assigned to the dwelling was found (0.197 [8]), again using final consumption expenditure. Finally, the share was scaled to the number of residents (2.54 [15][16]). For further information on the sharing of the safe operating space, see [15]. As shown in Equation 1, this sharing resulted in an assigned share of 3.74×10^{-11} available to one single family stand-alone dwelling out of the entire safe operating space as defined by the Planetary Boundaries. Finally, the impact score of each house (quantified by performing an LCA) was related to the assigned share of safe operating space and if the utilized vs. available operating space ratio was less than 1, the house was considered absolute sustainable.

$$\frac{1}{7.63\cdot10^{9}}\cdot0.571\cdot0.197\cdot2.54=3.74\cdot10^{-11}\quad(Eq.1)$$

2.1. The MiniCO2 Houses
The methodology was applied to a case consisting of five single family stand-alone dwellings known as the MiniCO2 Houses. In 2013, the Danish foundation Realdania developed these experimental houses with the goal of assessing strategies for reducing the GHG emissions in a building's life cycle. This was achieved by introducing five different sustainability strategies focusing on different aspects of a building's life cycle and applying one strategy to each house [17]. The five sustainability strategies resulted in the five houses - Upcycle House, the Innovative Maintenance-free House, the Traditional Maintenance-free House, the Adaptable House and the Quota House.

The first MiniCO2 House is Upcycle House. The strategy with Upcycle House was to reduce the GHG emissions from the product stage by using mainly upcycled, recycled and reused materials [18]. The strategy for the Upcycle House is in line with current tendencies towards circular economy where more recycled materials are being used, thus, avoiding extraction of virgin resources.

The strategy for the Innovative Maintenance-free House is low maintenance and an extended service life, hence reducing the amounts of GHGs emitted in the product stage. The Innovative Maintenance-free House has been designed to have a service life of 150 years by using materials that are *expected* to have long service lives and low maintenance demands [19]. This strategy is in contrast to the Traditional Maintenance-free House, which provides low maintenance and a long service life by using materials that are *known* to have a long service life of 150 years and low maintenance demands. The choice of materials, architectural and technical design of the Traditional Maintenance-free House are based on experiences on family houses located in Denmark [20].

The fourth MiniCO2 House is the Adaptable House. The strategy with the Adaptable House is flexibility and variability during the building's service life. The Adaptable House is designed to accommodate the residents' changing functional requirements throughout the building's service life by, for instance, facilitating/simplifying reconstructions and extensions of the house. This will save materials and energy used for reconstruction in the buildings use stage and thereby save GHG emissions in the building's life cycle [21].

The final MiniCO2 House, the Quota House, is designed to affect the behaviour of the residents to reduce energy consumption in the building's use stage and thus reduce the associated GHG emissions. This is achieved both through the architectural design and smart technologies integrated in the house. As example, the layout of the house takes basis in the orientation of the sun and daylight and thus reduces the need for electricity. At the same time, the integrated technologies help monitor and control the consumption of water, heat and electricity. The energy consumption is measured against a quota and rendered visible so that the residents are constantly aware of their energy consumption, which influences their behaviour and should reduce their consumption. Additionally, a sixth house, the Reference House, representing a standard single family stand-alone dwelling is assessed [22].

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The main difference between the MiniCO2 Houses is that they are designed to reduce impacts from different life cycle stages. The Upcycle House and Adaptable House are designed to limit impacts in the product stage, the Quota House is designed to reduce impacts in the use stage, while the two Maintenance-free Houses focus on reducing impacts in both the product stage and end of life stage.

Picture 1-5. The five MiniCO2 Houses. Picture 1, top-left: Upcycle House (UP). Picture 2, top-right: Innovative Maintenance-free House (IMF). Picture 3, mid-left: Traditional Maintenance-free House (TMF). Picture 4, mid-right: Adaptable House (AD). Picture 5, bottom-center: Quota House (Q). The Reference House (Ref) is not illustrated as it is a theoretical, standard house.

2.2. Life Cycle Assessment

The results of this study were found by performing an LCA following the standards ISO 14040:2006 and ISO 14044:2006. We defined a functional unit as to *annually house one family in a stand-alone dwelling in Denmark.* We assumed that all houses compared can fulfil this functional unit. Because the objective of the MiniCO2 Houses is to reduce GHG emissions, the impact coverage in this study is restricted to assessing climate change. Thus, conclusions about absolute sustainability are only in terms of climate change and environmental impact coverage must be expanded to provide a comprehensive AESA. All systems were modelled using the software tool SimaPro 8.9 [23] with the database ecoinvent 3.4 [24]. An outline of the system boundaries for the modelled systems are presented in Table 1 (for further information, see Supporting Information I in [15]).

Table 1. The overall system boundaries for the Life Cycle Assessment.

Life cycle stage	Included in the LCA
Product stage	All materials for constructing the buildings and waste thereof.
Use stage	District heating and electricity for ventilation. Estimations based on [25]. Replacements of building components/materials.
End of Life stage	All building materials for constructing the buildings were considered as waste.
Transportation	Average transportation processes for building materials and waste disposal in the Danish market.

The six houses are compared across two scenarios. In the first scenario, the Worst Case Scenario, all houses are assessed assuming that current practices are not improved thereby accounting for an expansion of the buildings, current consumption of heat, energy grid of 2018 (11.1 g CO2 eq per MJ heat and 668.7 g CO2 eq per kWh electricity) [26], current lifespan of materials and current End of Life routes (for further information regarding scenarios, see Supporting Information I in [15]). In the second scenario the houses are assessed according to a Best Case Scenario, i.e. no expansion of the buildings, a 25% lower consumption of heat relative to the Worst Case Scenario, an energy grid of 2030 with a larger share of renewable energy sources (9.0 g CO2 eq per MJ heat and 651.8 g CO2 eq per kWh electricity) [26], a doubled lifespan of the materials and finally a higher recycling rate for relevant materials (for specific lifespan and recycling rates of materials, see Supporting Information III in [15]). The Best Case Scenario is defined to represent a future with lower environmental impact compared to the Worst Case Scenario, representing current conditions. A full inventory for all houses can be found in [15] and [27]. The results obtained indicate the environmental performance of one house compared to the others and whether or not the houses are truly sustainable relative to an assigned share of the Planetary Boundaries For extensive results on other impact categories, see [15].

3. Results

The results of the six houses and life cycle stages obtained using the Planetary Boundaries-based Life Cycle Impact Assessment method are presented in Table 2.

Table 2. The characterised impact score obtained from the Planetary Boundaries-based Life Cycle Impact Assessment. The results are presented for each house and each life cycle stage. The life cycle stage with the highest impact score is marked in orange.
[a] 120 year service life
[b] 150 year service life

CC – Energy Imbalance [W m^{-2}]		REF[a]	UP[a]	TMF[b]	IMF[b]	AD[a]	Q[a]
Worst Case Scenario	Product stage	1.28×10^{-10}	6.06×10^{-11}	1.13×10^{-10}	1.27×10^{-10}	1.13×10^{-10}	1.42×10^{-10}
	Use stage	3.15×10^{-10}	3.05×10^{-10}	3.16×10^{-10}	3.81×10^{-10}	4.58×10^{-10}	2.92×10^{-10}
	End of Life stage	3.64×10^{-11}	4.71×10^{-11}	5.10×10^{-11}	2.72×10^{-11}	6.65×10^{-11}	3.36×10^{-11}
	Total	$\mathbf{4.80\times10^{-10}}$	$\mathbf{4.12\times10^{-10}}$	$\mathbf{4.81\times10^{-10}}$	$\mathbf{5.35\times10^{-10}}$	$\mathbf{6.38\times10^{-10}}$	$\mathbf{4.67\times10^{-10}}$
Best Case Scenario	Product stage	1.28×10^{-10}	6.06×10^{-11}	1.13×10^{-10}	1.27×10^{-10}	1.13×10^{-10}	1.42×10^{-10}
	Use stage	1.14×10^{-10}	1.06×10^{-10}	1.04×10^{-10}	1.33×10^{-10}	1.23×10^{-10}	1.01×10^{-10}
	End of Life stage	1.22×10^{-11}	1.32×10^{-11}	1.59×10^{-11}	1.83×10^{-11}	1.41×10^{-11}	1.70×10^{-11}
	Total	$\mathbf{2.54\times10^{-10}}$	$\mathbf{1.80\times10^{-10}}$	$\mathbf{2.33\times10^{-10}}$	$\mathbf{2.78\times10^{-10}}$	$\mathbf{2.50\times10^{-10}}$	$\mathbf{2.60\times10^{-10}}$

The results presented in Table 2 show that the use stage is the main contributor to the environmental impact irrespective of house and that the product stage is the second largest contributor in the Worst Case Scenario. In the Best Case Scenario, the use stage is the largest contributor for Upcycle House, Innovative Maintenance-free House and Adaptable House, while the product stage is the largest contributor for the remaining three houses. Moreover, in the Best Case Scenario it is seen that the use stage constitutes a considerably smaller part of the environmental impact compared to the Worst Case Scenario and thus the improvements introduced in the Best Case Scenario show to have an effect on the results. Furthermore, the impact potentials for the MiniCO2 Houses are compared to the share of safe operating space available to each dwelling (see Figure 1 and Table 3).

Table 3. The share of the safe operating space occupied by each of the houses in the Worst Case Scenario and the Best Case Scenario. The Planetary Boundary for the impact category Climate change (CC) – Energy Imbalance is 1 W m^{-2} and the share assigned to a single family stand-alone dwelling is 3.74×10^{-11} W m^{-2}. The darker the orange, the higher the impact.
[a] 120 year service life
[b] 150 year service life

		REF[a]	**UP**[a]	**TMF**[b]	**IMF**[b]	**AD**[a]	**Q**[a]
Worst Case Scenario	SoSOS occupied	32.2	27.7	32.3	36.0	42.9	31.4
Best Case Scenario	SoSOS occupied	17.1	12.1	15.6	18.7	16.8	17.4

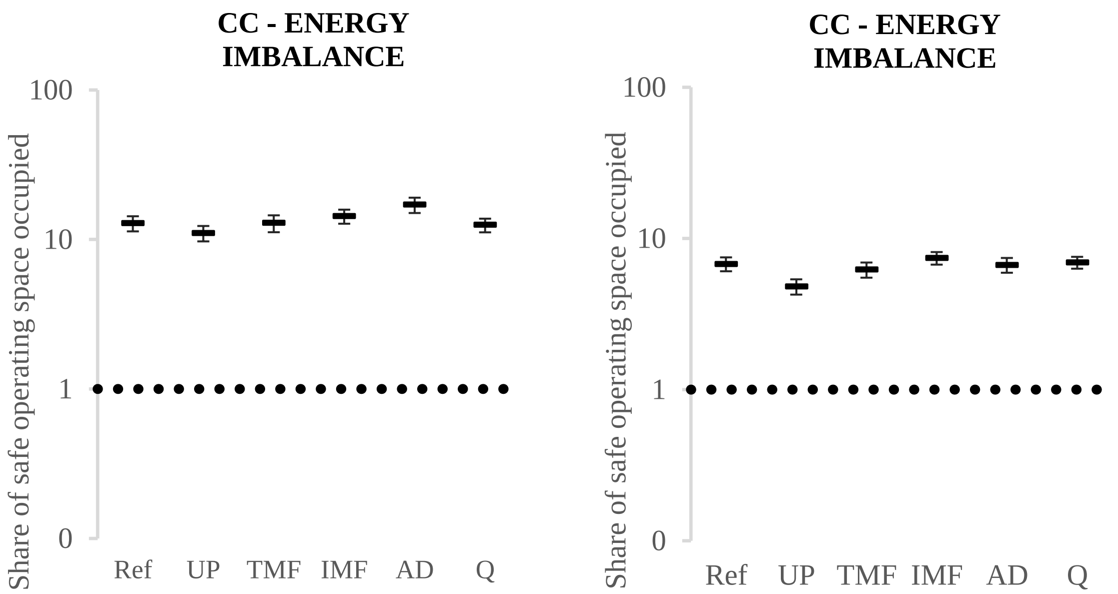

Figure 1. The impact potential for Climate Change - Energy imbalance relative to allocated share of safe operating space for each dwelling. Left and right figure reflects the Worst and Best Case Scenario, respectively. The environmental boundary is indicated by the dashed line and impact scores ≤1 can be considered sustainable. Error bars indicate the 95% confidence interval of the life-cycle inventory estimating using Monte Carlo analysis. Y-axis is on a logarithmic scale.

Figure 1 clearly shows that the impacts induced by all buildings exceed the assigned share of safe operating space irrespective of whether it is the Worst or Best Case Scenario. In the Worst Case Scenario the buildings exceed the assigned share of safe operating space by a factor 11.0 to a factor 17.0, Upcycle House being the house closest to stay within the boundary and the Adaptable House exceeding the boundary the most. In the Best Case Scenario the houses exceed the assigned share of safe operating space by a factor 4.8 to a factor 7.4, where again Upcycle House is closest to stay within the boundary and the Innovative Maintenance-free House exceeding the boundary the most. For further details on the impact contribution of processes and materials, as well as sensitivity analysis', see [15].

4. Discussion and conclusion

As described in Section 1, it is important that we keep the understanding of sustainability in mind when assessing environmental performance of products, systems or, in this case, single family stand-alone dwellings. If future generations shall be able to meet their own needs as we and previous generations have met ours, it is crucial that we do not settle for “lower” but instead strive for “low enough” in terms of induced environmental impact. While these buildings all represent an important step towards lower environmental impacts, the results presented in the previous paragraph indicate that even more effort is needed to design absolute sustainable houses. The results indicate that the focus should be on the use and product stage as these were found to be the most contributing life cycle stages.

The results presented in the previous paragraph show that the environmental impact potentials does differ between the houses depending on the approach to (environmentally) sustainable building design. However, as this difference is not extensive, it is uncertain which design strategy is the most efficient when seeking to reach a sustainable level. The results do however indicate that the changes implemented in the Best Case Scenario, i.e. energy grids, End of Life routes and consumption patterns etc. cause the houses to perform considerably better compared to the Worst Case Scenario. These observations reveals that the changes made in the Best Case Scenario does influence the results positively in terms of reaching sustainability in the built environment. However, since the houses even in the Best Case Scenario exceed the boundary considerably, the results indicate that it is unlikely that the houses can be considered absolute sustainable unless we improve dramatically on all parameters. Additionally, this conclusion is supported by uncertainty regarding the impact estimates for electricity and heat in the use stage, which are found to lower than comparable estimates [28]. This difference could cause that the impact in the use stage to be underestimated, which ultimately would result in a larger impact for each dwelling and thereby being even further from reaching a sustainable level. Hence, all stakeholders involved with the built environment need to acknowledge and take on the task of building more sustainable buildings. It is likely that this issue goes beyond the building sector and that all actors in our society, i.e. consumers, industries and politicians alike, need to mobilize to overcome this challenge.

Absolute sustainability is an approach that allows us to understand the actual distance to target in terms of environmental performance. The approach is still relatively new and some questions therefore remain unanswered in terms of application. The assignment of the safe operating space which was briefly described in Section 2 is a major challenge in assessments of this type. It has a potentially crucial impact on the results [29], but subjectivity is most likely impossible to avoid when trying to decide who has the right to impact how much. This assignment of the safe operating space should be kept in mind when interpreting the results. If a consensus could be reached on how to share the safe operating space in a fair way, it would be possible to assign the boundaries and thereby reach a per-square-meter impact allowance for buildings which would ensure absolute sustainability. Such a benchmark for environmental performance could potentially be implemented in certification systems or building regulations to facilitate that new buildings are designed to be environmentally sustainable and not just better than the existing building stock.

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